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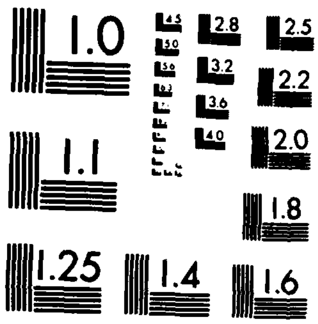

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The modifications to three major facilities at Caltech, carried out in preparation for an extensive investigation of shock enhanced mixing and combustion in supersonic combustion ramjets, has progressed according to schedule. This work is complete on the GALCIT 17-inch shock tube and on the Unsteady Combustion Facility, and they are operating as planned. Extensive improvement of the optical diagnostics and data acquisition equipment for both of these is nearly complete. Design of the new heated-hydrogen leg for the Hydrogen/Fluorine facility has been simplified considerably from the original concept and is progressing satisfactorily. Extensive computational studies of the interaction between weak shock waves and isolated regions of hydrogen embedded in air has revealed a behavior which suggests that considerable technological advantage may accrue by the use of multiple weak shocks to enhance mixing. Keywords;

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1. RESEARCH OBJECTIVES

The general aim of the first year's effort under the subject grant, concerned with the experimental part of the program, has been the construction and modification of the three large facilities involved and the development of instrumentation and data acquisition systems. This is entirely according to our proposed plan; the only experiments that have performed are those to check operation of equipment and instrumentation. The computational studies, however, have proceeded as planned to delineate the areas of prime experimental interest.

(a) Investigations in the GALCIT 17-inch Shock Tube.

It is the long-term objective of the shock tube investigation to study in detail the rapid mixing process induced by the impingement of a weak shock wave upon an isolated cylindrical volume of hydrogen or helium. These two-dimensional nonsteady results may be interpreted to apply to the steady three-dimensional problem directly relevant to supersonic combustors.

The test section of the shock tube has been rebuilt and extended to accomodate experiments covering more than two milliseconds duration; new windows have been built and installed to provide access for the new laser based optical investigations. The large dye laser has been acquired and the experimental biacetyl fluorescence technique has been successfully tried under conditions for which it will be employed. The CID camera and the video recorder have arrived and have been incorporated into the experimental setup.

(b) Experiments on Combustion in Large Vortices.

These experiments, to be carried out in our Unsteady Combustion Facility, are designed to investigate the detailed combustion processes in large vortical structures, simulating the strong streamwise vortices generated by the interaction of a weak shock wave with a streamwise flowing hydrogen jet. They are essentially the complement of the shock tube investigations described under (a).

This effort has required the complete redesign of the combustion chamber and gas supply system. The design and construction of the new equipment is now finished and preliminary tests have confirmed proper functioning of the siren-device for periodic generation of vortices. The optical system has also been rebuilt and employs some of the instrumentation and data acquisition system discussed under (a). The work on this task is on schedule.

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(c) Analytical and Computational Studies.

These studies explore weak shock wave interaction with hydrogen jets over a wide range of conditions, both as a guide to the most appropriate sets of physical conditions for experiment and to determine other possible phenomena that had not been evident in the previous experiments and the rather limited results from earlier computations. The extensive program of Euler code computational studies has gone according to schedule, accomplishing not only the original aims but also revealing a portion of the interaction that was not previously apppreciated. This involves a tendency for each of the streamwise vortices to split, one carrying the preponderate portion of the vorticity. This result suggests that a second shock interaction with the weaker of these structures would have the considerable technological advantage of increasing the strength and improving the distribution of streamwise vorticity, with a corresponding improvement in mixing rate.

(d) Hydrogen/Fluorine Facility Development.

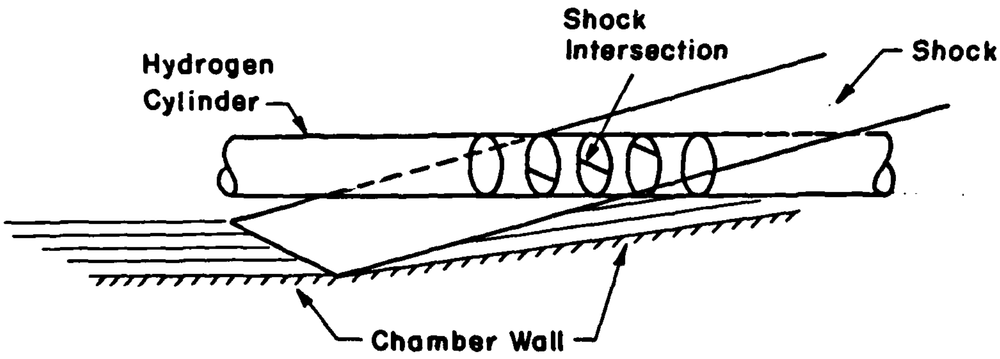
The aim of this task was to design and construct a heater and the associated control equipment to permit a supersonic shear layer between hydrogen and fluorine to be studied in this facility. This will allow not only the first thoroughly detailed study of a reacting supersonic shear layer but should permit a comparably thorough study of the effects of shock interaction with this layer.

As the design work on the heater loop progressed, it became clear that a concept, different from that originally planned, had such a marked advantage that the new design has been pursued and will be implemented. This task is proceeding according to schedule.

2. STATUS OF RESEARCH

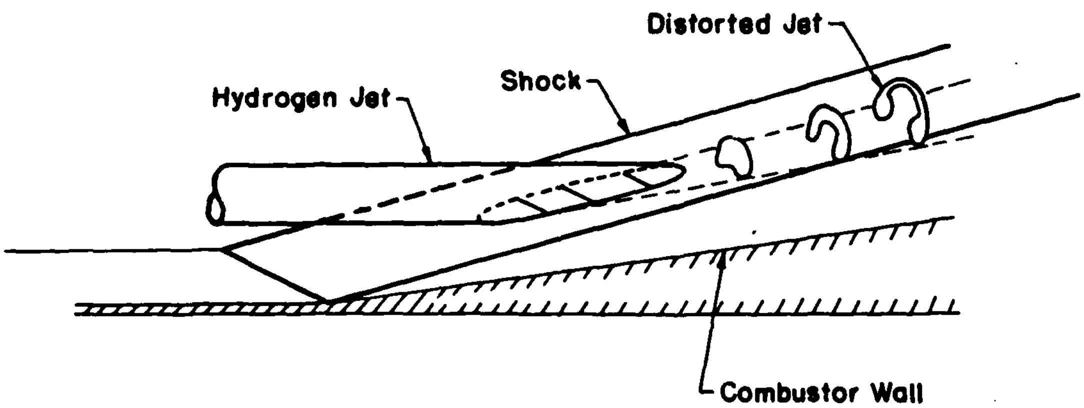
(a) Investigations in the GALCIT 17 inch shock tube.

The experiments to be carried out in the 17 inch shock tube aim to investigate the first stages of shock enhancement of mixing and combustion of hydrogen in a supersonic combustor. To fix ideas, consider a jet of hydrogen in a supersonic stream of air, Fig. 1, which is intersected by a weak shock generated by a very low angle wall ramp.



1. Sketch of Oblique Shock Intersection with Hydrogen Jet

Because the density of the hydrogen is so much lower than that of the air, the hydrogen jet is turned through a larger angle than the air, Fig. 2, a strong vortex pair is formed and very rapid mixing ensues.

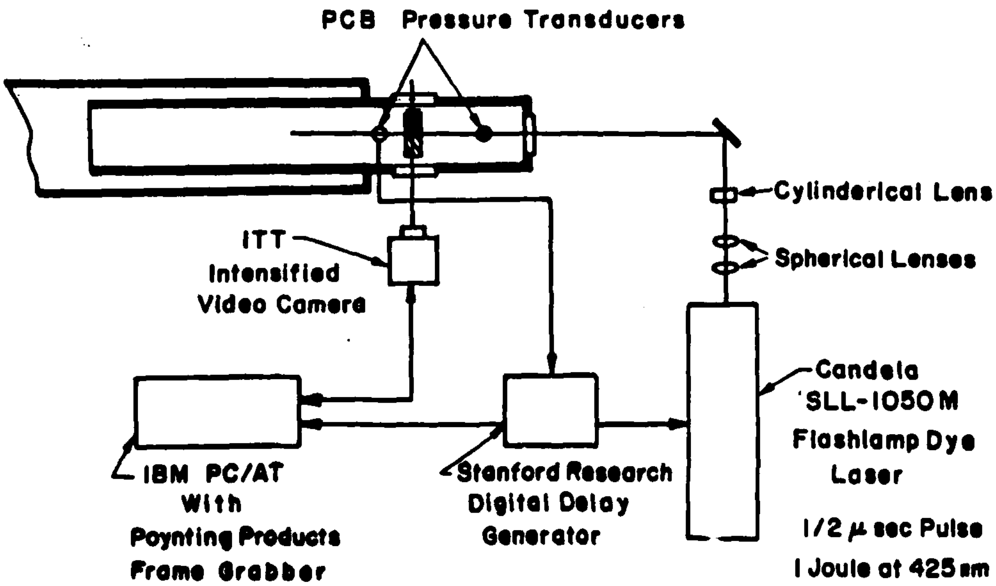


2. Jet Distortion Produced by Shock Impingement

The results of shock tube experiments are interpreted as the flow induced in a plane normal to the flow moving with the gas velocity and hence replaces the three-dimensional steady flow with a two-dimensional time-dependent flow.

In these experiments, we are examining the rapid mixing process induced when a weak shock wave propagating through air impinges on a cylindrical region filled with helium. The helium gas initially is contained within a very light weight microfilm membrane prior to shock impingement. The effort during the first year has been directed toward final definition of the experimental approach, the the design and construction of the experimental apparatus and the modifications to the shock tube. The optical techniques to be employed in the experiment constitute a vital part of the program. Three different techniques will be employed: shodowgraph photography, laser induced fluorescence and laser induced phosphorescence. These three techniques are intended, respectively, to map the development of the flow field, to trace the progress of mixing of helium into the surrounding air, and to trace the molecular mixing between helium and oxygen. The progress in these efforts is described below.

<u>The Shock Tube</u>- The shock waves used in these experiments are being generated in the 17 inch diameter shock tube, and the region of interaction between shock waves and the helium filled cylinder is placed within a 27 cm square text section inserted into the rear of the shock tube. This square test section is about 2 meters long and 1.2 meters is inserted into the circular test section. A sketch of the shock tube working section and the arrangement of the optical equipment is shown in Fig. 3. The use of



3. Shock Tube Working Section and Optical Arrangement

a square test section will allow optical access more easily than in the 17 inch circular section because of the flat sides of the test section. The reduction in area from the 17 inch circular section to the 27 cm square section will not restrict the experiments.

Work on the 27 cm test section has been completed and it is now being used. Optical access is possible through two windows located on either side of the section and through an additional window which is built into the downstream end. The latter window makes possible illumination of the test area from that end for the dye tests described below.

<u>Flow Visualization</u>- Shadowgraphy is one of the techniques being used to examine the flow and this method will be used extensively to study the development of the flow as and after the shock wave impinges on the helium filled region. The apparatus, including mirrors, stands and optical tables, required to take shadowgraph photographs in several modes, is presently in hand. The first mode is to take a single photograph during each firing of the shock tube. Several spark light sources are available now for these tests which have a duration of less than a microsecond and a spark light sourse with a 20 nanosecond duration has been ordered. It will be available for this work by the end of October, 1987.

A second technique used in studying the flow field utilizes a motion picture camera with a framing rate of 150,000 frames per second to photograph the shadowgraph images; with this test technique about 50 frames can be obtained during each test. The resolution of the pictures will be less than that for the individual spark photographs.

<u>Fluorescence of Biacetyl</u>- Biacetyl is a relatively well known dye which, when illuminated with radiation in the visible region, produces fluorescence radiation at a different wave length of the visible region. Dye will be added to the helium, a shock will be passed through the air and allowed to impinge on the helium, and after a predetermined time delay, a pulse of laser light in the form of a thin sheet will be passed through the gas. The resulting fluorescent radiation will be measured with an intensified video camera with a line of sight which will be alligned perpendicular to the sheet of light and data will be examined subsequently to determine the distribution of the dye and hence of the helium. This experiment must be repeated for a substantial sequence of time delays to establish the development of the mixing process as a function of time.

The results of this investigation will give an accurate time resolved picture of the distribution of the dye as a function of the time and hence the distribution of the light gas, providing we can ignore the differences in the diffusion rates of the dye and the helium. By changing the thickness of the sheet of light we can average our results over a thin or thick section of the region of interest. Both have advantages and we will use both.

The minimum thickness of the sheet will allow us to illuminate a physical region of about 0.1 cm in depth. The resolution of the camera, which will have an array of pixels about 244 by 388 will limit the dimensions of the smallest area we can observe to about the same dimension. Therefore, the data which can be obtained with this technique cannot be used to address the question of molecular-scale mixing of the light and heavy gas. However, given the original scale of the light gas region of 2 to 3 cm, the 0.1 cm scale available will give us an excellent determination of the gross mixing.

Biacetyl fluorescence has been used in the past by a number of experimentors, e.g. Epstein (1977), and we believe that this is a relatively low risk technique which will substantially add to the data we can obtain from shadowgraph photography. The principal problem here is getting enough light from the fluorescence of the biacetyl dye to allow us to obtain the distribution of the dye. Based on previous expeience and the equipment we propose to use, we expect no problems.

<u>Biacetyl Phosphorescence</u>- This technique will allow us to address the issue of molecular scale mixing. This technique is based on the fact that when appropriately excited molecules such as benzene or acetone collide with biacetyl molecules they can transfer energy to the biacetyl molecules and cause them to phosphoresce. Thus, if benzene vapor is placed in one gas, and biacetyl dye in the other, phosphorescence can be produced only in areas in which the two fluids have mixed on the molecular scale. Benzene molecules can be excited by irradiation with ultraviolet light but the phosphorescence will be in the visible range.

This technique will be used in our experiments by placing biacetyl dye in the helium and benzene in the surrounding air. After the passage of the shock wave through the helium, the benzene will be excited by passing a sheet of pulsed laser-light through the test section and the phosphorescence from the biacetyl dye, which is excited by the benzene, will be recorded. The phosphorescence radiation is emitted over times of the order of a millisecond and an exposure time for the camera must be of the order of microseconds in order to stop the motion of the gas. Thus, only a small fraction of the phosphorescence radiation can be used. As a consequence, this is a higher risk experiment than the biacetyl fluorescence because of two processes which limit the radiation available for measurement. One is that energy must be passed to the biacetyl molelcules though collision with benzene molecules. The other is that only a small part of the phosphorescence radiation can be used because we want to keep the exposure time of the camera down to a few microseconds.

The instrumentation to carry out biacetyl phosphoresence is not substantially different from that required for the fluoresence experiment. The ultraviolet light required to excite the benzene can be obtained by using the same laser as that required for the fluoresence using a nonlinear crystal to double the frequency of the

light. One new window will be required because the ultraviolet light will not pass through the windows used for the longer wave length light used in the fluorescence experiments. However, the same camera and optics can be used to observe both phosphorescence and fluorescence.

The apparatus required to carry out the the fluorescence experiment with the biacetyl dye is currently in hand except for the image intensified CID camera. We are now using an identical CID camera which, although it is not intensified, is being used in the development of our experimental techniques. We have completed the data acquisition system which will be used to manipulate the video pictures obtained with the cameras. Software development for the data acquisition system is underway.

(b) Experiments on Combustion in Large Vortices.

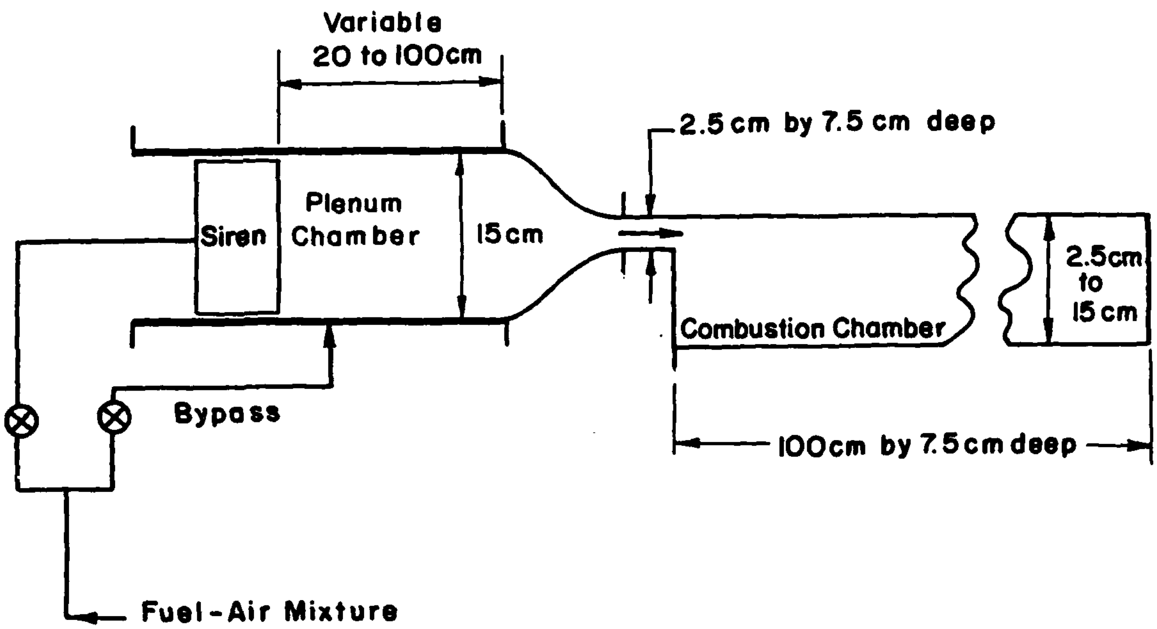
One of the tasks that is being carried out under the URI grant is the design and construction of a new test duct for the proposed experiments. Our aim is to develop an apparatus in which it is possible to produce vortices at the interface between burnt gas and a fresh fuel air mixture and to observe the influence of various fluid dynamic and chemical parameters on the rate of combustion in these vortices.

One of the parameters we want to observe is the light emitted during the combustion process, which is a good measure of the local volumetric heat release by the combustion process. We shall do this with a camera based on a charge injected device which has an array of 380 by 240 pixels and employs a gated image intensification system which is required to sense the low light levels produced by the combustion of methane and air. This system will allow us to observe a region of about 15 cm by 24 cm with useful resolution and requires about 100,000 data points per picture. The data acquisition rate required to follow the developement of a vortex with this camera is over 100 million per second and is larger than our system can accomodate. Hence, we shall observe a periodic sequence of vortices and use a phase averaging technique.

Based on our experience in the combustion instability experiment, we have chosen to use the same rearward facing step geometry to produce the vortices. However, we have modified the combustion duct so that we may control the frequency and growth rate of the vortices. In addition we have increased the depth of the test section so that the vortices can grow to a much larger scale before being influenced by the lower wall of the combustion chamber.

New Test Facility- A schematic diagram of the new test facility is shown in Fig.4. The most evident change in the combustion chamber is the use of a duct with a height that can be varied bewtween 2.5 and 15 cm. The maximum depth will allow vortices to reach scales of 10 cm before the inteference effects of the lower wall becomes important.

In the previous experiments, the frequency of the oscillation selected by the instability was one of the acoustic modes of the system and the mode selected was a complex function of the length of the plenuim chamber, the geometry of the rest of the system and the chemical parameters of the fuel-air mixture. In the present apparatus, we shall use this result to our advantage by controlling the length of the plenum chamber to fix the frequency of one of the acoustic modes to match the desired frequency. We gain further control over the frequency of the vortex shedding by using a siren, placed at the upstream end of the combustion chamber, to excite the duct at the desired frequency. The amplitude of the energy supplied by the siren to the desired mode can be varied by passing part of the fuel-air mixture through the siren and part through a bypass around the siren.



4. Diagram of New Experimental Facility

This system will allow us to control the amplitude and frequency of the velocity and pressure fluctuations at the flame holder lip. Thus, we shall be able to control the frequency of vortex shedding from the lip. Furthermore, our previous work has shown that the rate of growth of the vortices is a function of the amplitude of the fluctuations at the flame holder lip. The bypass arrangement which we have provided for mixture injection allows us active control of the amplitude as well as the frequency of the fluctuations and thereby control the rate of growth of the vortices. The apparatus will produce vortices at frequencies between 100 to 600 Hz and will allow us to observe vortices with scales up to 15 cm. Construction has been completed, and initial tests are in preparation.

Instrumentation- The primary new item of instrumentation is the gated image intensified CID camera which will be used to measure the light emitted by the combustion process and thus to estimate the rate of heat release throughout the vortex. Photographs will be obtained at a frequency of 30 frames per second and will be stored an a VCR. Later, individual frames will be selected from this video movie with a frame grabber, and the intensity data will be digitized for further analysis.

In addition, we will use a new LDV system to measure one or two velocity components throughout the flow field. This Disa system with a single velocity component capability was acquired during the 1986-87 contract year and the two component system will be completed early in the 1987-88 contract year.

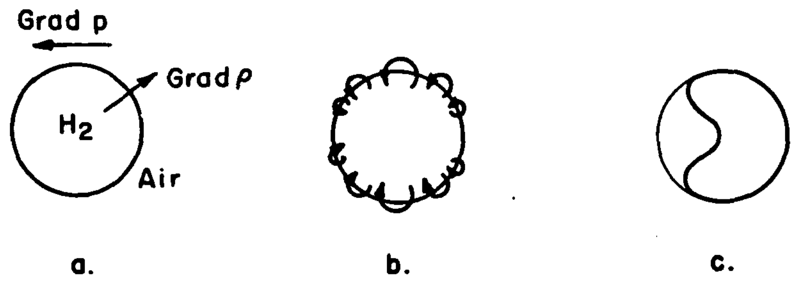
Other parameters measured will include: the velocity fluctutation at the flame holder lip, obtained with a conventional hot wire system; pressure and pressure fluctuations on one wall of the duct; single frame shadowgraph pictures; and 8,000 frames per second shadowgraph movies. Finally, we have developed an ion probe which will allow us to determine the ion density in a volume of gas corresponding to a 1 millimeter cube. Because the regions where combustion is taking place are also regions in which the gas is highly ionized, this insturment will be used in conjunction with the flow visualization techniques to make certain that we can define the regions of active combustion accurately.

This research task is also supported, in part, by AFOSR Grant AFOSR 84-0286.

(c) Analytical and Computational Studies.

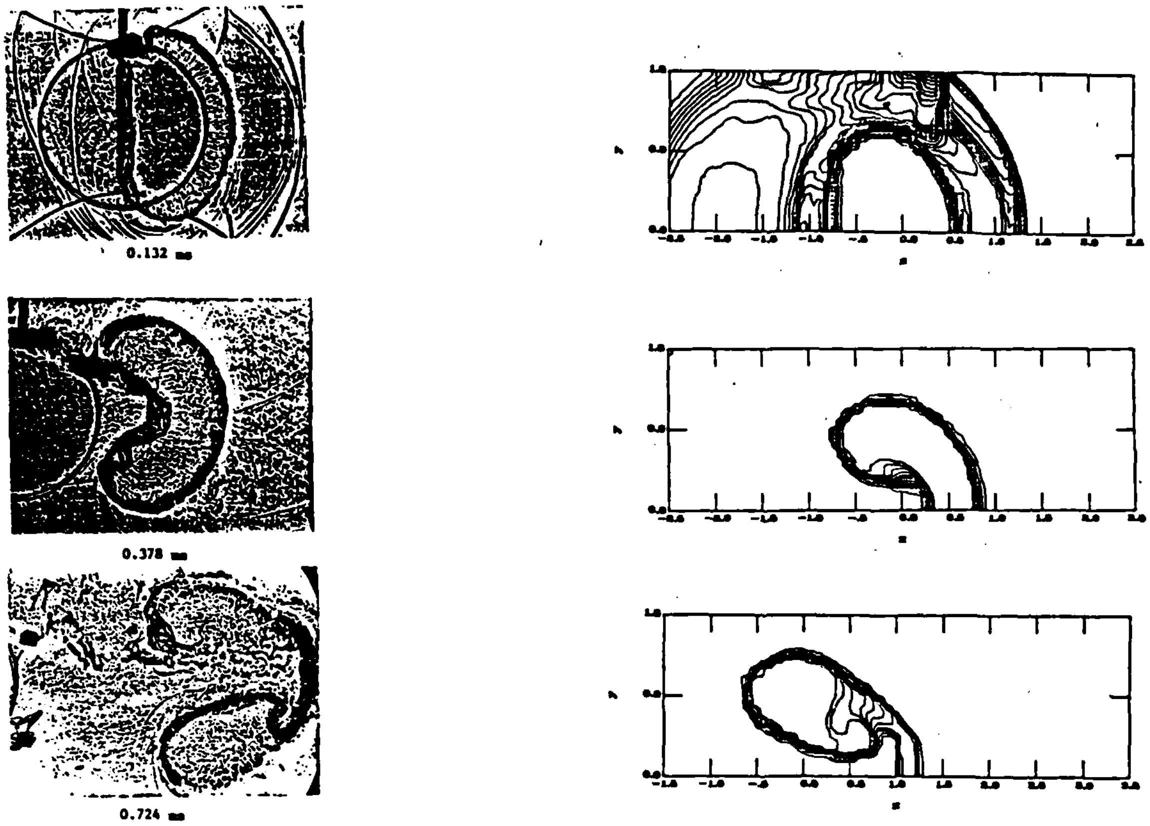
Analytical and computational studies of the interaction between weak shock waves and localized regions of hydrogen embedded in air constitute a particularly important task in the early phases of this grant. Their aim is to explore a wide range of interaction conditions and, from these results, to determine those areas especially fertile for detailed experimental investigation. The Euler code employed and the general accuracy of the results have been discussed by Marble et al (1987), and further modifications of that code were employed in the results to be examined here.

The initial configuration consists of a plane cylindrical region of helium situated symmetrically between two horizontal planes of infinite length. A plane shock approaches from the left, passes over the inhomogeneous region, and sets up the events sketched in Fig. 5. The shock constitutes a strong, concentrated pressure gradient which is generally not colinear with the density gradient of the inhomogeneity, Fig. 5a. The consequence is a generation of vorticity at the interface between the two gases, Fig. 5b and the resulting distortion of the interface as shown in Fig. 5c. Figure 6a shows the upper half of the density contours



5. Vorticity and Distortion Induced by Shock Passing over Hydrogen Cylinder in Air.

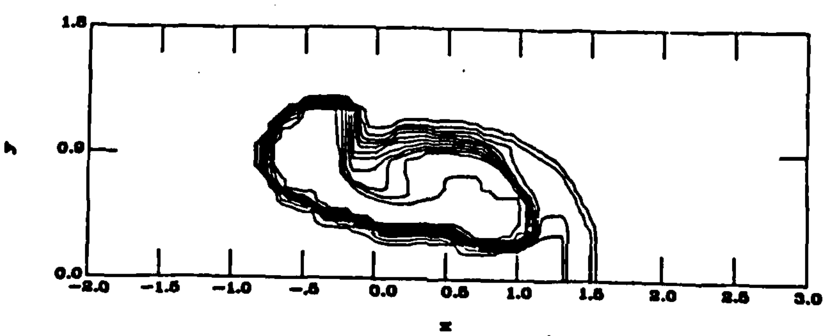
calculated for three values of time after shock passage. These results were obtained before the award of the present grant. They may be compared with shadowgraphs of the corresponding shock tube results given in Fig. 6b.



(a) (b)

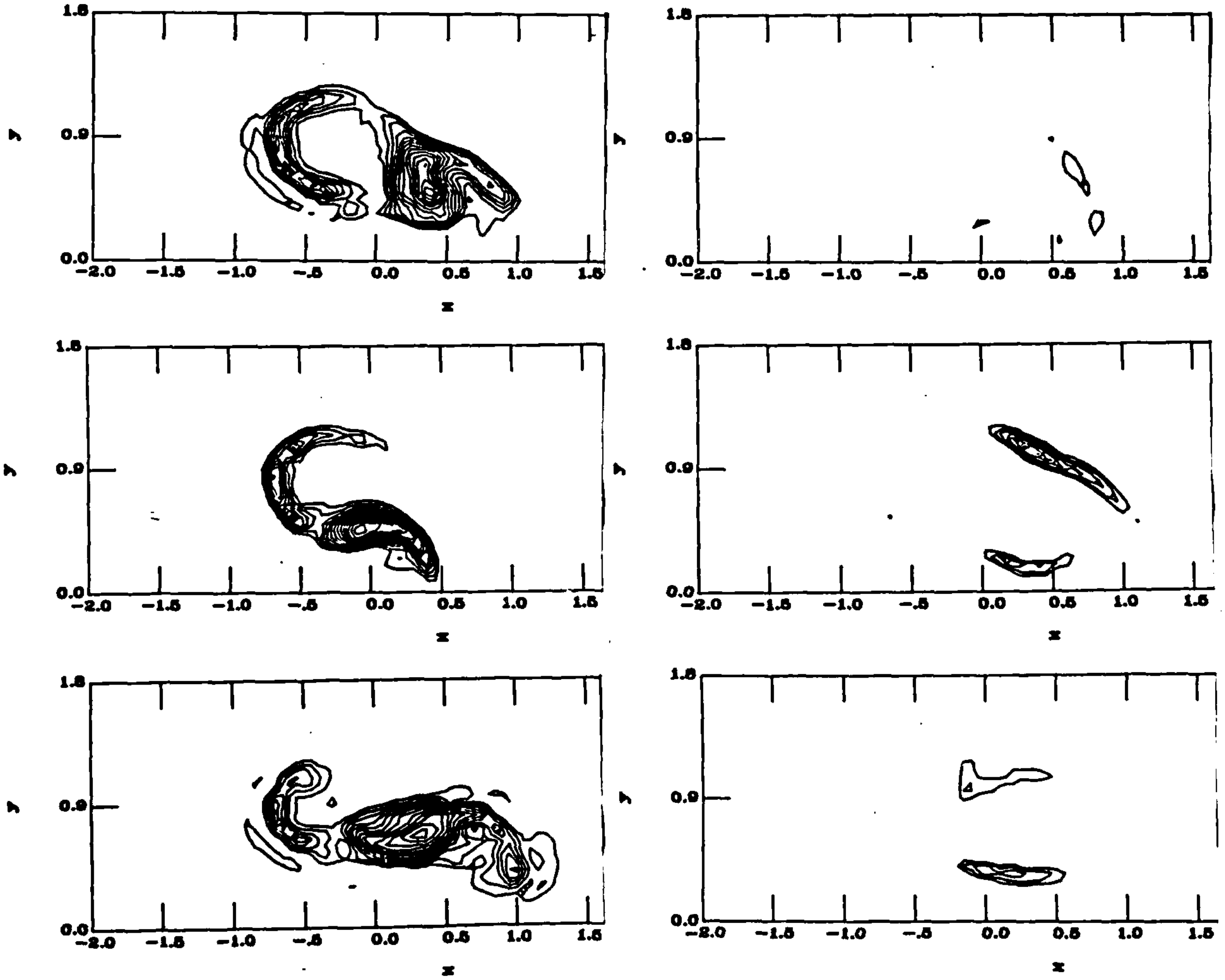
6. Computations and Shadowgraphs of Shock Interaction.

During the first year of the contract period, 1986-87, calculations of this type have been extended to much longer times after shock interaction, as well as to include the calculation of characteristics other than the density. One notable phenomenon was the tendency for a portion of each vortex of the vortex pair to separate itself from the remaining portion of the hydrogen mass and to move downsream, in the direction of shock motion, with a considerably higher velocity. Such a motion is indicated by the density contours of Fig. 7 computed for a time 50% longer than the last density contour shown in Fig. 6. This effect has been observed very conclusively in subsequent calculations, Winkler et al (1987).



7. Density Contour Showing Separation of Hydrogen Masses.

The mechanism underlying this behavior has been examined in some detail and was found to be the migration of the vorticity, generated by shock inpingement, toward a small portion of the hydrogen at the downstream region of the inhomogeneity. This behavior was discovered by computing the vorticity distribution at a sequence of time values and observing the vorticity flux. Now in the upper half of the symmetric flow field under discussion, the vorticity is predominantly counter-clockwise. Part way through the migration process, however, vorticity of the opposite sign was being formed. It appeared possible that this vorticity might grow to cancel the initial vorticity and effectively terminate the mixing enhancement.



8. Positive and Negative Vorticity at Three Time Values.

Upon detailed examination of the pressure and density fields, it transpired that the reorganization of the density field and the pressure field induced by the velocities were, in some regions, oriented so as to generate clockwise vorticity and hence to cancel some initial vorticity. Figure 8 shows the distributions of positive and negative vorticity at three time steps through the process.

The first result of this investigation, as suggested by the diagrams of Fig. 8, indicates that the fields quickly reorganize themselves to terminate the further vorticity generation, and the portion of the hydrogen which drifts away more rapdily contains the bulk of the initial vorticity. This latter portion of the hydrogen is therefore the dominant beneficiary of the mixing enhancement.

The second result follows from the fact that the remaining portion of the hydrogen retains a small portion of the vorticity and may therefore benefit by a second shock impingement. This suggests the importance of considering multiple shock impingement as a means of depositing strong streamwise vorticity more uniformly over the hydrogen mass.

(d) Hydrogen/Fluorine Facility Development.

Considerable progress has been realized during the reporting period, the main component of which is a simplification of the design on which the original proposal was based. The design presently being implemented will achieve the same goal of roughly doubling the enthalpy of the supersonic stream but will avoid the potentially risky, in terms of the resulting flow quality, in-line heat exchanger, that would have been used as a "topping/trimming" heating element, just before the entrance to the supersonic test section settling chamber.

In the adopted design, all the enthalpy is added to the supersonic stream reactant (fuel) mixture prior to the short run time, by raising the temperature of the whole reactant tank, valves, regulators, etc. to the desired value. This will be accomplished using electrical strip heaters bolted to the tank and piping, and using closed loop control/monitoring system. This process will typically require overnight heating of the tank (at essentially atmospheric internal pressure) with the introduction of the fuel (hydrogen) reactant and remaining diluent, a relatively short time prior to the run itself, to allow for the reactant mixture to homogenize in composition.

Roughly 10% of the volume of the tank will be taken by aluminum screen packing. Accordingly, we note that the associated drop in temperature of the tank/packing material, as the gaseous reactants/diluents are introduced, will be small, as their heat capacity will be considerably smaller than that of the tank/packing material. At this writing the high pressure reactant tank and the heating system have been ordered, with delivery expected towards the end of the calendar year.

Progress has also been realized in another area. One of the main design concerns from the very beginning revolved around the short run time pressure regulation requirements. Initially, we explored the possibility of using a Digital Valve. Considerable risk,however, remained in predicting its performance (not to speak of its cost which would have exceeded our budgeted amount). Since this is a crucial facility component as regards the overall success of the effort, we decided to undertake a pilot study based on a more promising in-house throttling valve design.

A first phase of this work, in which a scaled prototype was designed and fabricated, has been completed and we are sufficiently encouraged to now regard this as our candidate solution to this problem at this writing. The present design for the throttling valve pressure regulator envisages a computer-controlled real-time digital actuator that progressively opens the throttling valve so as to maintain the required upstream stagnation pressure. We are

presently investigating various actuation/drive/computer-interface possibilities. We expect to have completed this phase by the end of the first quarter of 1988. We should note that if our in-house efforts reveal hitherto unsuspected difficulties, the Digital Valve option remains in effect.

This progress has been documented in a GALCIT internal report, Hall, Dimotakis, Papamoschou & Frieler (1987), which is being maintained as a running document as the details of the facility design and fabrication evolve.

Closely related to this design effort has been a finite kinetics analysis of supersonic shear layer combustion. This was initially undertaken as a pilot study to assist us in assessing the range of chemical kinetics effects (Damkohler numbers) we should expect (or could explore) in the facility, in order to make sure that the range of interest in this parameter could be properly covered. As we progressed with this analysis, however, we realized that some of the issues were generic as they relate to supersonic combustion. Accordingly, we submitted a paper summarizing our findings, Dimotakis & Hall (1987) . In that study both the $H_2/NO/F_2$ chemical system, of interest in this research effort, as well as the H_2/air chemical system were studied.

This effort has been supported, in part, by AFOSR Grant 83-0213.

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4. PERSONNEL

Faculty

F. E. C. Culick
P. Dimotakis
T. Kubota
F. E. Marble
B. Sturtevant
E. E. Zukoski

Research Fellows

G. J. Hendricks
J. Jacobs
R. Miake-Lye
D. Papamoschou
T. Sobota

Graduate Students

J. Budzinski
C. Frieler
J. Hall
J. Yang
M. T. Yueng
T. Zsak

5. INTERACTIONS WITH INDUSTRIAL AND GOVERNMENTAL GROUPS

Professor Culick continues frequent exchange of information on combustion instability with groups at Wright- Patterson Air Force Base, Johns Hopkins Applied Physics Laboratory, and the McDonnell-Douglas Research Laboratory. Professor Culick is also serving as a member of the external advisory committee on the Shuttle boost rocket re-design.

Professor Dimotakis has, within the past year, carried out discussions concerning supersonic mixing and combustion with workers of the Johns Hopkins University, Applied Physics Laboratory (Dr. Fred Billig). He has maintained a continuous close relationship with the Combustion Research group of the Scandia Livermore laboratory. Professor Dimotakis also expects to be active in the supersonic mixing and combustion effort associated with the SCRAMJET development work at the Rocketdyne Division, Rockwell International.

Professor Kubota has been in discussion with Rocketdyne Division, Rockwell International, on hypersonic computational and experimental problems concerned with the SCRAMJET inlet boundary layer and heat transfer problems. He recently completed a visit to the NASA Langley Research Center to discuss future experimental work on hydrogen injection and mixing directly related to the SCRAMJET development for the National Aerospace Plane.

Professor Marble serves as a member of the Air Force Studies Board, Committee on Hypersonic Technology for Military Applications and the Hypervelocity Mixing Advisory Group, NASA Langley Research Center. He also has close association with NASA Lewis Research Center on problems of turbomachinery, combustion and turbine cooling. In addition, he spends extended periods with the Gas Turbine Laboratory of the Massachussetts Institute of Technology. Professor Marble is Consultant to the Northrop Aircraft Division, TRW Inc. at the Norton Air Force Base, to the Rocketdyne Division of Rockwell International and to the Technical Systems Division, Aerojet General Corporation.

Professor Sturtevant has a working relation with Lawrence Livermore Laboratory on problems of shock dynamics related to fusion reactor fundamentals. He has also close contacts, through Dr. J.-F. Haas, w th the French Center for Atomic Energy. As a result of the extensive hypersonic activity now underway at the Rocketdyne Division of Rockwell International, Dr. Sturtevant will be working closely with them on the development of their hypersonic experimental facilities. These facilities will be an essential component in the development of their SCRAMJET engine and engine inlet. Dr. Sturtevant has frequent interaction with the computational group at the Los Alamos National Laboratory; they have recently performed extensive calculations on the interaction of shock waves with gas inhomogeneities.

Professor Zukoski serves as an advisor and consultant to the U. S. Air Force on the problems of hydrogen combustion and explosion in the exhaust duct of the S.S.M.E. engine at the Vandenburg Satellite Launching Facility. He maintains contact with the Aero Propulsion Laboratory, Wright-Patterson Air Force Base concerning problems of ram jet and afterburner instability. Recently Professor Zukoski has been in contact with the Aerojet Technical Systems Division concerning their work on the NASP propulsion system. He has recently had contact with the Rocketdyne Division of Rockwell International and expects to be involved in some aspects of their SCRAMJET engine.

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